Exposures to particles and volatile organic compounds across multiple transportation modes

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Our Belief

When it comes to the pursuit for improved air quality, we believe in the power of clarity, transparency and integrity. With real-world data we can meet emissions challenges – instilling trust and confidence in our industry partners and public.

It's with our commitment and independence we are able to make a significant contribution toward positive change and to achieve enduring results.

Introduction

- Founded in 2011, headquartered in the UK
- Operations in UK, Germany, USA and South Korea
- Independent testing house specialising in real-world emissions testing
- Over 2,500 vehicles/machines tested across passenger, commercial and off-road
- >100 tires tests, >100 vehicle interior tests
- Largest commercially available database of real-world emissions data
- Work with regulators, OEMs, Tier 1/2 suppliers, fuel and chemical companies, fleets
- Chair of EU CEN Workshops 90 and 103
- Honorary Research Fellow, Imperial College London

Agenda

1. Objectives and methodology
2. Measurement equipment
3. Test route
4. Volatile organic compound (VOC) exposures
5. Particle and carbon dioxide (CO_2) exposures
6. Conclusions and suggestions for further study

Objectives and methodology

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Project and funding

- Funded by the TRANSITION Clean Air Network through the first round of its Discovery & Innovation Fund in 2021
- TRANSITION is a UK-wide network, led by the University of Birmingham in collaboration with nine universities and over 20 cross-sector partners, aiming to optimise the air quality and health outcomes of transport decarbonisation.
- The network (NERC ref. NE/V002449/1) is itself funded by UK Research & Innovation through its Clean Air Strategic Priorities Fund, administered by the Natural Environment Research Council.

Question and approach

- Cleanest way from London Paddington to Oxford city centre – 85 km direct
- Not designed for multiple repetitions
- First pass to see where issues exist
- Measurements made in May 2021

Route	Day	Vehicle
Electric/diesel train, Paddington to Oxford	1	GWR Hitachi Class 800
Diesel bus, Oxford to London	1	Alexander Dennis Enviro400
Underground, Paddington to Waterloo	2	Mark 2 1972 Stock
Diesel train, Waterloo to Basingstoke	2	South Western Railway Class 159
Diesel train, Basingstoke to Oxford	2	Virgin Cross Country Class 220 Voyager
Hybrid bus, Oxford	2	Alexander Dennis Enviro400 Electric Hybrid
Diesel internal combustion engine car	3	2012 Mercedes-Benz C-Class C220 CDI BlueEfficiency SE G-Tronic Estate
Underground, Paddington to Victoria		As above and 2009 Stock
Diesel coach	4	Alexander Dennis 34 Plaxton Panorama
Battery electric vehicle	5	2021 Vauxhall Corsa E SRI NAV Premium

Equipment

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Measurements – volatile organic compounds

- Two-dimensional gas chromatography with mass spectrometry from
- INSIGHT flow modulator from SepSolve Analytical for separation
- BENCH-TOF time-of flight mass spectrometer
- Thermal desorption from Markes International

Measurements – particles and carbon dioxide

- Condensation Particle Counter for particle number
- Laser scattering for particle mass
- Non-dispersive infra-red for carbon dioxide
- From National Air Quality Testing Services of the UK

Test route

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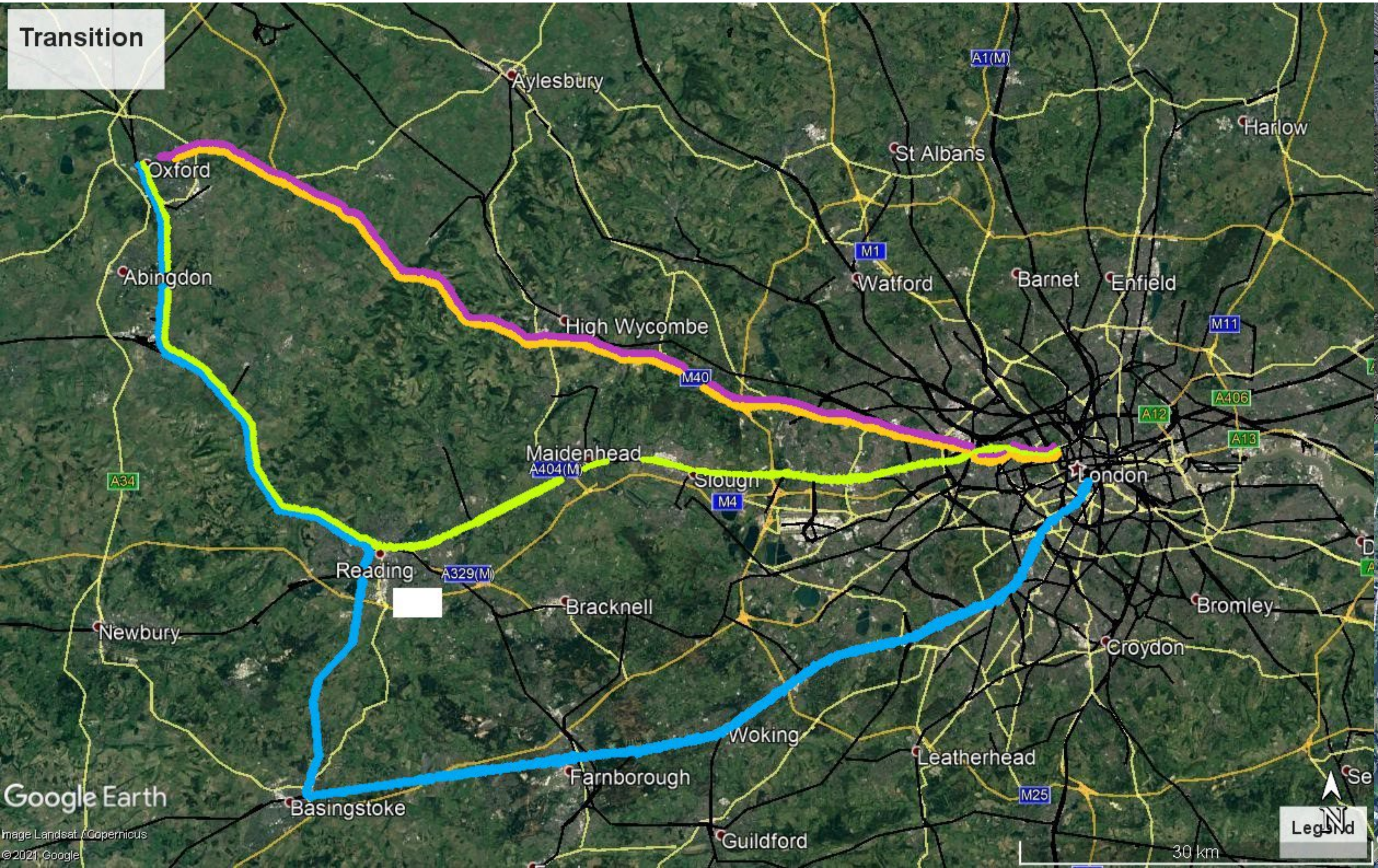
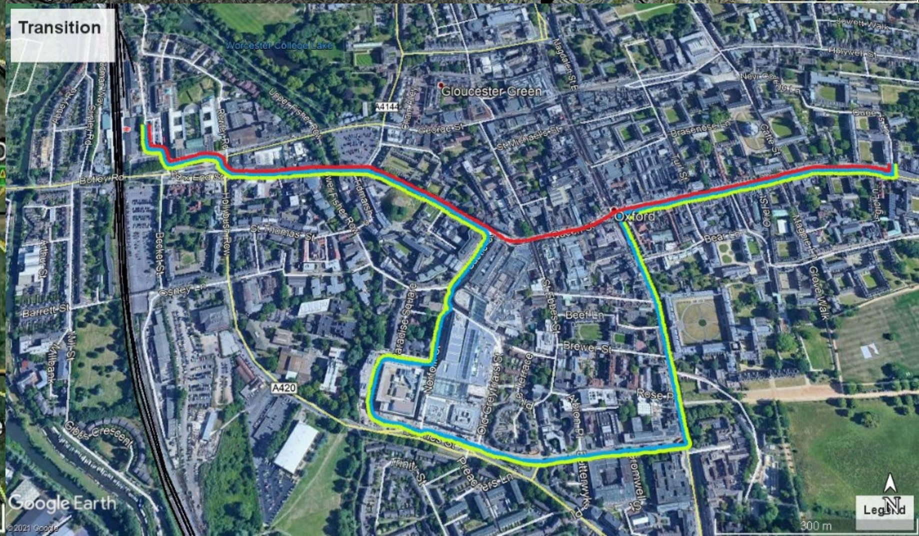
Test routes

	Deliverable 1	Electric/diesel public transport
	Deliverable 2	Diesel public transport
	Deliverable 3 and 5	Internal combustion engine vehicle/battery electric vehicle
	Deliverable 4	Diesel coach service
	Deliverable 6 and 7	Walking and cycling





Volatile organic compounds

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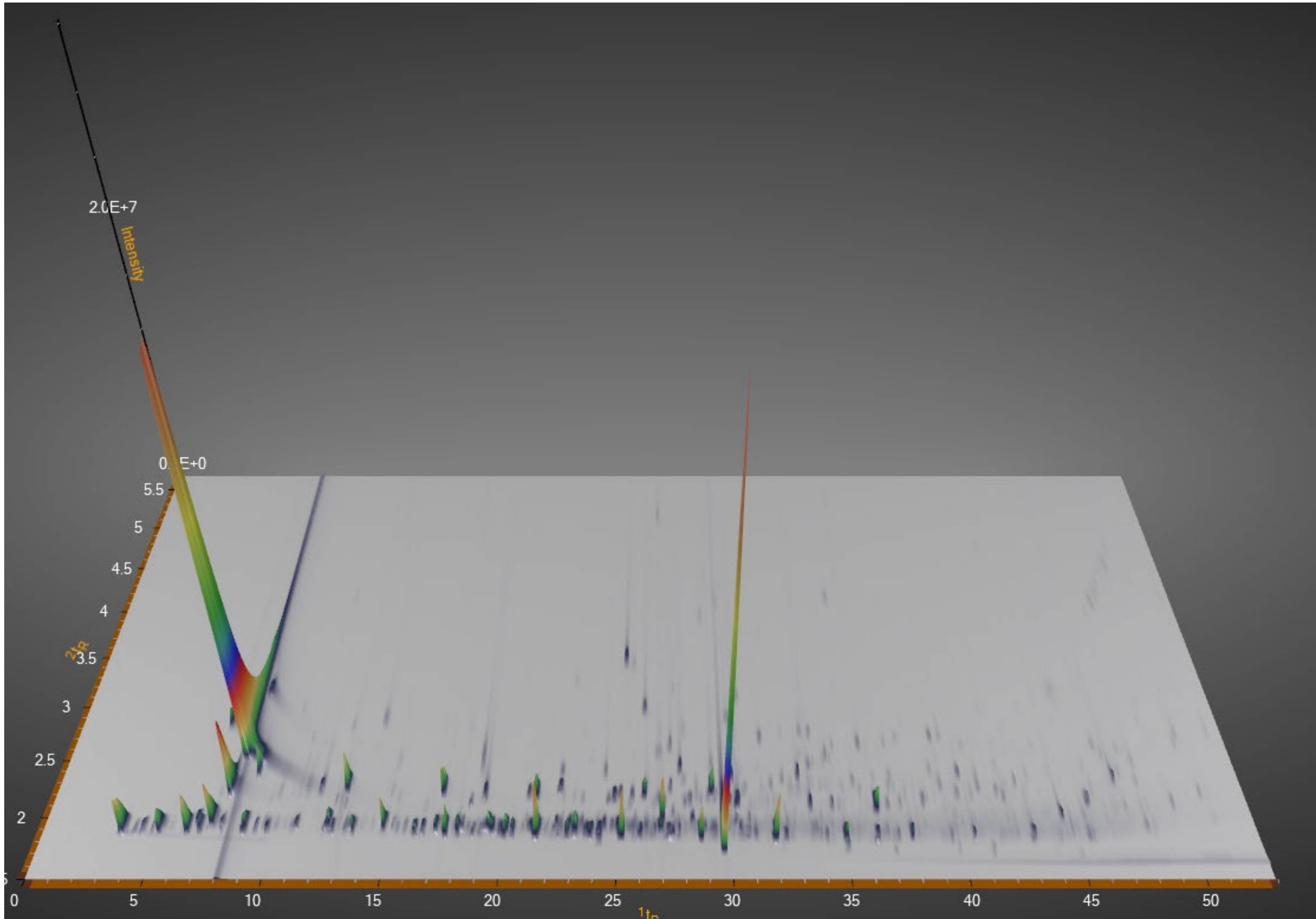
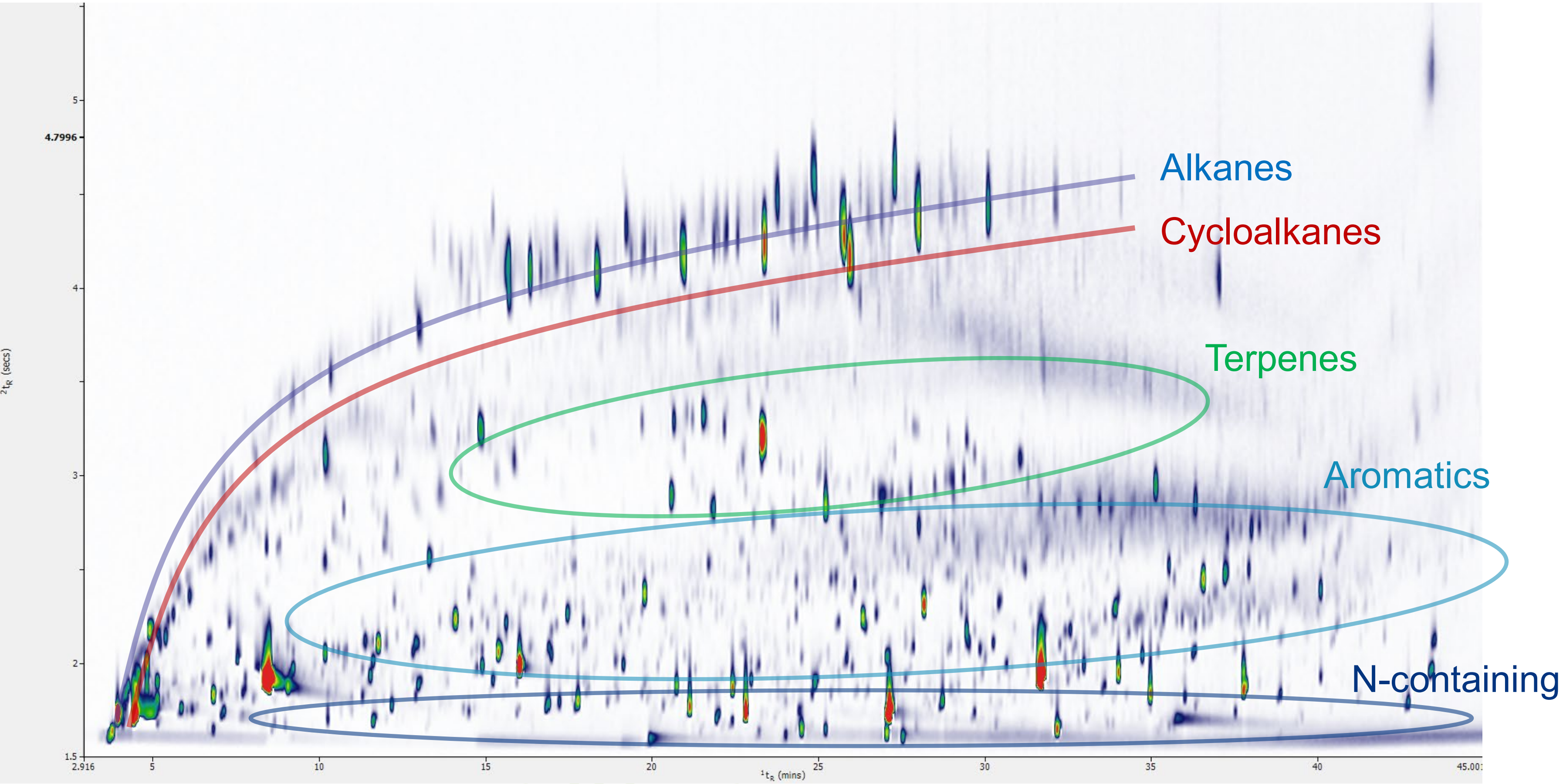
Electric/diesel train chromatogram

- Two dimensional separation required to understand range of emissions
- Compound identification using NIST spectral library
- Semi quantitation indicated by height of each peak



PIMS vehicle interior air quality testing

Functional group classification



- Wide-ranging analytes identified
- Alkanes: lungs, liver, kidney, brain
- Cycloalkanes: headaches, dizziness
- Terpenes: aromas
- Aromatics: carcinogens
- N-containing: carcinogens

Functional groups and respiration rates

- Product of measured concentrations, breathing volume and journey length
- Coach emissions are amplified by relatively slow speeds
- Foot and bicycle relatively low despite peaks and respiration level, due to dilution

Mass (µg)	Alcohols	Alkane, alkene, alkyne and cyclo-	Aromatics + Aldehydes and Ketones	PAH and Nitro-containing group	Total	Breathing volume (l/min)	Duration (minutes)
Paddington platform	12.5	3.0	1.5	0.2	17.3	10	13
Electric/diesel train - Paddington to Oxford	40.0	22.9	7.9	44.5	115.4	8	80
Bus - Oxford Station to Queens Lane	32.7	8.4	3.7	1.1	45.9	8	14
Underground - Paddington to Waterloo	12.2	15.3	5.1	1.7	34.4	10	25
Diesel train - Waterloo to Basingstoke	24.1	25.8	5.2	3.9	59.0	8	93
Diesel train - Basingstoke to Oxford	45.2	54.4	12.4	5.5	117.5	8	57
Station to QL & back by Bus	23.9	7.4	3.1	0.7	35.1	8	48
Underground - Paddington to Victoria	7.1	7.4	3.3	2.4	20.2	10	33
Coach - Victoria to Oxford	23.1	173.6	34.0	30.4	261.1	8	191
Foot - Oxford Station to Queens Lane	103.2	50.3	21.8	15.8	191.1	40	39
BEV - Paddington to Oxford Station	48.7	128.0	12.4	7.2	196.2	8	87
Foot - Oxford Station to Queens Lane	34.1	38.1	15.9	12.3	100.4	40	90
Diesel ICE - Paddington to Queens Lane	31.0	16.8	5.1	4.5	57.3	8	89
Foot - Oxford Station to Queens Lane	1.1	15.5	6.2	3.4	26.3	40	33
Bicycle - Oxford Station to Queens Lane	5.7	13.2	20.4	3.5	42.8	60	17

Speciation

- 275 compounds discovered in total
- Top 12 shown
- Many arise from other people
- Pollution from other vehicles a secondary source
- Range of potential health effects to humans and fish, but
- Actual health effects unknown

Compound, peak area (Volt.minute)	Formula	Electric /diesel train	Diesel train	Coach	Electric car	Diesel car	Active	Potential source	Health risk
n-Nonadecanol-1	$C_{19}H_{40}O$	31,467	82,411	588,561	251,618	13,449	13,719	Personal care	n/a
Nonadecane	$C_{19}H_{40}$	48,984	65,968	261,851	478,118	63,450	25,910	Diesel component	Lung irritation
1-Octanol, 2-butyl-	$C_{12}H_{26}O$	24,763	85,514	293,671	459,293	24,202	19,637	Personal care	Aquatic
Cyclopentasiloxane, decamethyl-	$C_{10}H_{30}O_5Si_5$	63,221	596,697	109,205	1,645	7,099	4,262	Personal care	Aquatic
1-Eicosanol	$C_{20}H_{42}O$	3,035	12,065	268,822	312,332	8,832	7,412	Personal care	Eye irritation, aquatic
Cyclotetrasiloxane, octamethyl-	$C_8H_{24}O_4Si_4$	32,882	127,592	98,984	128,910	42,925	121,542	Personal care	Aquatic
Carbon dioxide	CO_2	109,617	138,458	57,950	95,709	53,434	95,425	Human respiration	At high concentrations only
Behenic alcohol	$C_{22}H_{46}O$	109,034	74,575	239,396	40,040	33,315	16,417	Personal care	n/a
4-Amino-1-butanol	$C_4H_{11}NO$	230,623	236,771	7,648	9,418	2,353	2,203	Personal care	Skin burns, eye damage
Oxirane, tetradecyl-	$C_{16}H_{32}O$	989	38,465	187,526	227,471	12,724	5,404	Lubricant, additive	Skin, eye irritation, potentially carcinogenic
p-Xylene	C_8H_{10}	14,533	31,586	140,257	71,692	2,561	181,258	Plastics, polyester	Skin, eye, lungs irritation, aquatic
Tetradecane	$C_{14}H_{30}$	15,715	34,727	237,061	65,668	10,133	16,470	Diesel component	Lung irritation

Source apportionment

- Inspect each compound individually and research most likely single source
- Coach is particularly high in personal care products and combustion emissions
- Diesel car is much lower than electric car, probably due to age and quality
- Electric/diesel train had relatively high plastics emissions

VOC grouping, peak area (Volt.minute)	Electric/diesel train – Day 1	Diesel train – Day 2	Coach – Day 3	Electric car – Day 4	Diesel car – Day 5	Active – Day 6
Personal care	684,492	1,529,328	2,195,457	1,607,962	225,222	280,237
Fuel and lubricants	249,938	469,090	1,370,762	1,304,455	172,667	184,939
Synthetic fibres, plastics	213,364	44,094	279,664	73,797	3,565	181,499
Human respiration (CO_2)	109,617	138,458	57,950	95,709	53,434	95,425
Total	1,257,411	2,180,971	3,903,833	3,081,924	454,888	742,099

Particles and carbon dioxide

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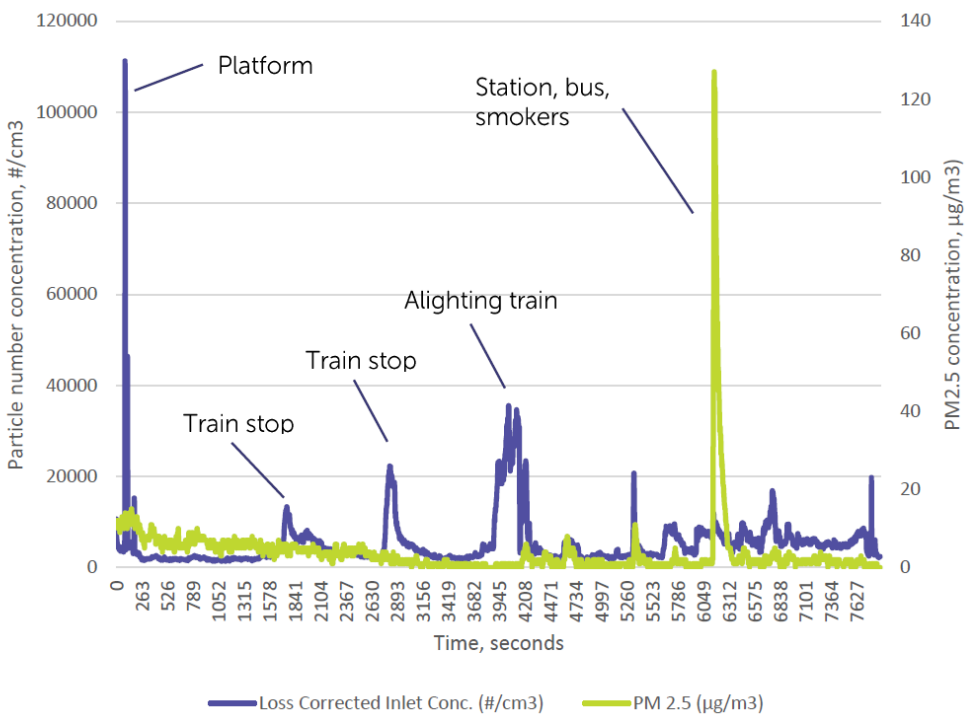
Paddington to Oxford via electric/diesel train

- Direct train, with power source changing mid-way
- Lower background in train than bus and foot
- Train stations have significant PN spikes
- Smoking is bad

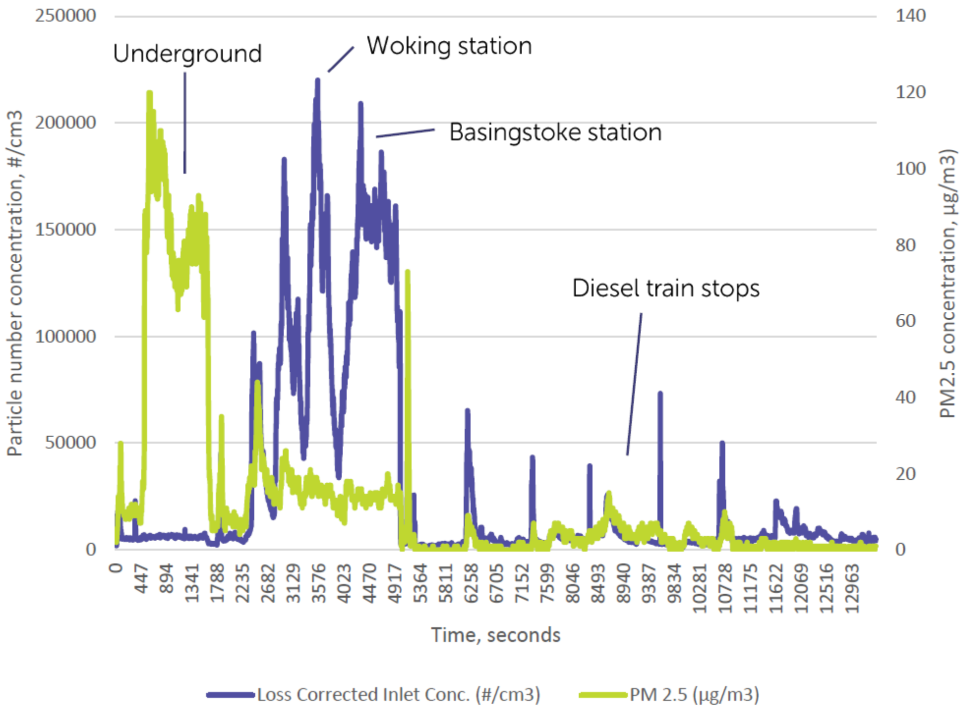
Segment	Start time (seconds)	End time (seconds)	Average PN (#/cm³)	Average $PM_{2.5}$ (µg/m³)	Average CO_2 (ppm)
Platform	0	780	4,114	8.37	403
Electric/diesel train	780	4,260	5,748	3.22	456
Platform	4,260	5,580	3,145	1.58	369
Bus	5,580	6,300	6,351	10.45	380
Foot	6,300	7,020	6,922	2.21	371
Bus	7,020	7,860	5,414	1.39	380
Total	0	7,860	5,271	3.82	413



Paddington to Oxford via diesel trains

- London Underground has high PM, not PN
- Two diesel trains, changing at Basingstoke, where high PN and PN experienced
- Smaller spikes at intermediate stations

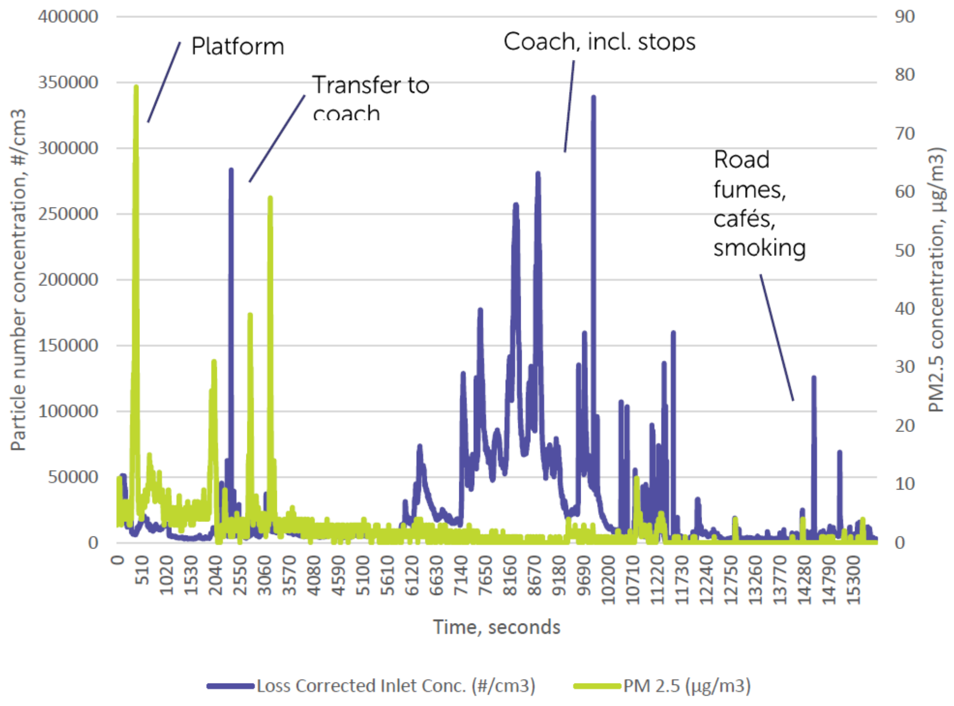
Segment	Start second	End second	Average PN (#/cm3)	Average PM2.5 (µg/m3)	Average CO_2 (ppm)
Platform	0	300	6,266	10.56	329
Underground train	300	1,200	6,204	70.63	323
Platform	1,200	1,500	5,819	80.63	331
Diesel train	1,500	4,680	77,478	17.68	353
Platform	4,680	7,080	25,965	3.67	303
Diesel train	7,080	10,200	5,886	3.89	436
Platform	10,200	10,500	2,748	2.64	423
Bus	10,500	13,380	7,384	1.17	309
Total	0	13,380	26,754	12.86	352



Paddington to Oxford via diesel coach

- Underground to Victoria, then coach
- Large PM and PN exposures at interchange
- High PN inside coach, likely to be combination of stops and ingress of road pollution
- PN spikes at coach stop and high street

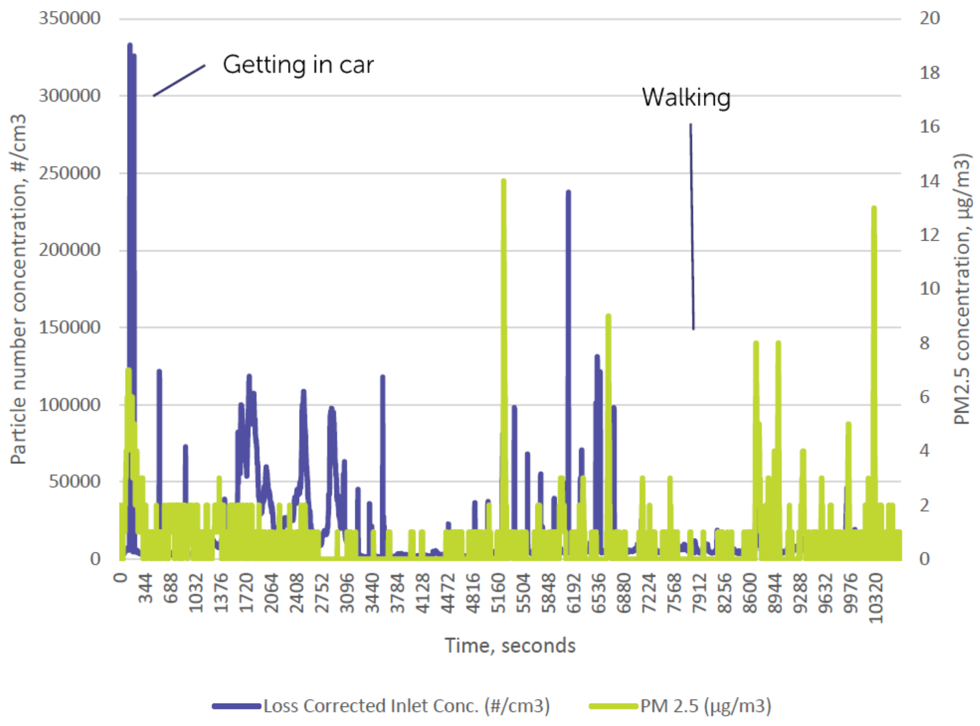
Segment	Start second	End second	Average PN (#/cm3)	Average PM2.5 (µg/m³)	Average CO_2 (ppm)
Platform	0	240	33,471	5.43	400
Underground train	240	1,980	8,146	8.73	424
Foot	1,980	3,420	11,240	6.47	402
Coach	3,420	13,440	31,363	1.11	444
Foot	13,440	15,780	5,606	0.11	396
Total	0	15,780	23,174	2.36	430



Paddington to Oxford via battery electric vehicle

- Getting in the car at Paddington has highest exposures
- Very low PM in the car, with some PN spikes from traffic pollution ingress
- Mixed exposures to PM and PN during walking depending on location

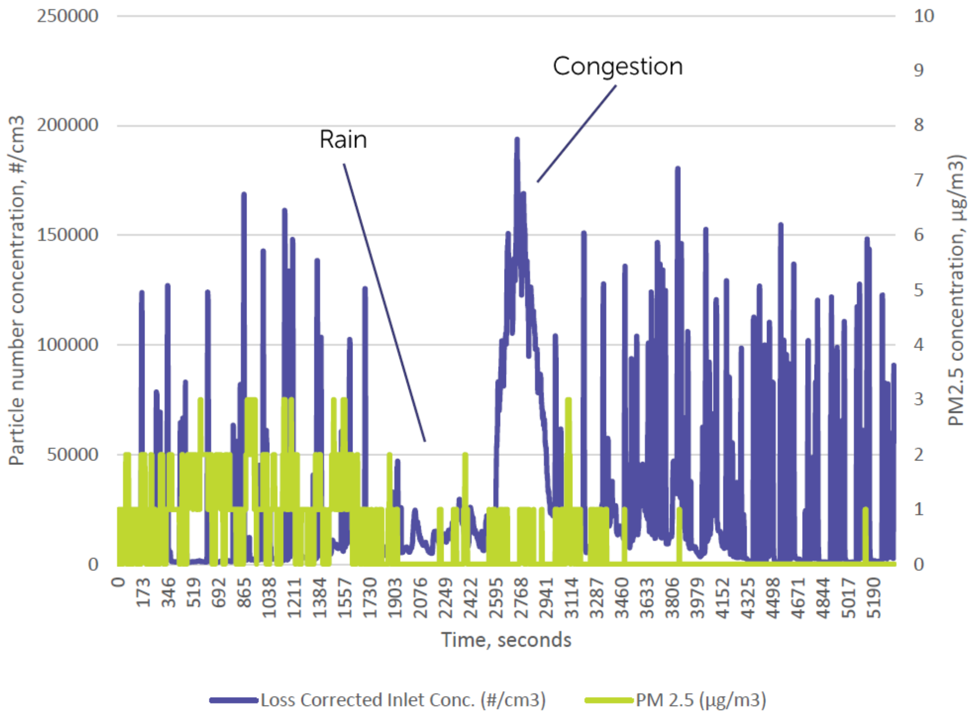
Segment	Start second	End second	Average PN (#/cm3)	Average PM2.5 (µg/m³)	Average CO_2 (ppm)
Platform	0	240	33,471	5.43	400
BEV	240	5,220	17,206	0.64	312
Foot	5,220	10,620	7,905	0.65	241
Total	0	10,620	12,437	0.65	277



Paddington to Oxford via diesel internal combustion engine car

- Door-to-door in car
- Older but premium diesel car
- Lowest exposures overall
- Rain suppresses particle pollution
- PN spikes correlating with road congestion

Segment	Start second	End second	Average PN (#/cm3)	Average PM2.5 (μg/m³)	Average CO_2 (ppm)
ICE	0	5,340	24,491	0.44	388
Total	0	5,340	24,491	0.44	388



Conclusion

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Summary by mode

Generic group	Average PN concentration (#/cm3)	Average PM concentration (μ/m3)	Average CO2 concentration (ppm)	Observations
Diesel train	77,478	17.68	353	Poor filtration, but fresh air
Coach	31,363	1.11	444	Ultrafines a problem; stuffy
ICE	24,491	0.44	388	Little mass, all ultrafines
BEV	17,206	0.64	312	High ultrafines, fresh air
Platform	11,647	16.13	366	More large than small PM
Cycling	10,375	1.68	391	Ambient PN, little mass
Foot	7,590	2.25	362	Ambient PN, little mass
Underground	7,175	39.68	373	Worst for larger particles
Bus	6,383	4.34	356	More large than small PM
Electric/diesel train	5,817	3.55	446	Highest CO_2 mode
Average	13,563	10.22	374	

Observations

- Trains are mixed: generally good inside, but bad in stations and at interchanges
- 18% to 29% of total exposure getting on and off trains
- Hybrid train had highest exposure to aromatic compounds
- Coach was subject to traffic pollution and at interchanges, and slow
- In both trains and coach, plastics from interior materials were measured
- Underground travel was dominated by larger particles – metals and human detritus
- Cars are generally good as they are point-to-point and quick
- Walking and cycling are exposed to big spikes, but diluted heavily overall

Implications and further work

- Journeys typically involve high variations in exposure concentrations
- Priority to clean up stations and interchanges ahead of upgrading rolling stock
- Improve filtration and ventilation on coach
- Allow cars to go point-to-point, subject to congestion constraints
- Extending range of active travel will have value
- Restrict smoking and food cooking

➢ Need to reproduce results

➢ Focus on specific problem areas for further research

CWA17934

- New standardised methodology for measuring in-cabin pollution
- Product of CEN Workshop 103
- Measurement of PN ingress and CO_2 build-up
- Light-duty vehicles
- Real on-road protocol
- Metric is ratio between external and internal concentrations – proven repeatability

➢ Objective to compare between different vehicles or different filters

Thank you.

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We're fast on our feet so we can conduct emissions testing when and where we're needed.

